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Females are now flying combat aircraft in the Air Force. Questions of gender differences regarding adaptation and performance in the high-G environment (9G) must be studied scientifically. The Dynamic Environment Simulator, a three-axis centrifuge with closed-loop flight simulation, provides the laboratory to investigate these issues. Results. The eight women in this high-G performance study did not show cardiovascular adaptation to high-G, whereas the eight men did. Both genders showed increased leg calf compliance indicating possible chronic vascular effects. No echocardiographic evidence of heart damage was found. The women demonstrated half the strength of the men, but displayed similar G tolerance and endurance. The women showed less oxygen desaturation of brain tissue than the men during high-G exposure. The women did not perform the simulated air-to-air combat sortie quite as well as the men, though there was no effect of menstrual cycle on their ability to complete the mission. There was also no effect of high-G exposure on the length of the female monthly cycle, regardless of oral contraceptive use. Conclusion. Women demonstrated acceptable tolerance to and performance during simulated high-G aerial combat, without menstrual effect, even in light of their reduced muscular strength and cardiovascular adaptation as compared to men.

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FOREWORD

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INTRODUCTION

Nature of the Problem

The critical issues addressed in this research are combat readiness and mission completion capability in squadrons that include female fighter pilots. At the time of this writing, thirteen females are flying high performance aircraft in the US Air Force. Eight additional are currently in training. Military members of both genders recognize that combat experience is still considered a requirement for promotion to true command positions and that fighter aircraft are considered the elite. Thus ambitious women will continue to pursue combat fighter experience. Unless the Combat Exclusion Law is reinstated, this trend is expected to increase, then stabilize, such that seven to ten percent of fighter pilots will be female across the services. Unfortunately, little or no data exist on female performance at high sustained acceleration (7-9 G). It is essential that questions of gender differences regarding adaptation and performance in the high stress environment of the modern fighter cockpit be studied scientifically. It is not known yet what percentage of the female fighter pilot population will choose to be on oral contraceptives, and thus both types of hormonal status must be examined. It is also imperative that women pursuing such a career be made aware of any real additional performance challenges they may experience during certain phases of their menstrual cycle or if they are taking oral contraceptives. Squadron commanders need to be aware of any potential compromises in female fighter pilot performance, if any, as a result of menses or medication.

Much research has investigated the complete loss of cognitive ability related to G-induced loss of consciousness [1, 2, 3, 4] but little is known about the effect on complex task performance during continuous self-administered exposure to sustained acceleration (high-G). The effects of sustained acceleration on women and their performance in a fighter cockpit are mostly unknown. Our previous report to the Defense Womens Health Research Program (DWHRP) revealed no reasons why women should not be permitted to fly in high-G aircraft, however the female volunteers were unable to perform the complex flying task as well as the males enrolled in our study [5]. This report is a Phase II effort, built on the shoulders of our previous performance work, to examine the following five physiological issues concerning women:

- Study of female cardiovascular adaptation to repeated exposure to high-G as compared to that of males.
- Study of female cardiac function before and after chronic high-G exposure as compared to that of males.
- Study of female centrifuge subjects' isometric strength before and after acute high-G exposure as compared to that of males.
- Study of female arterial & cerebral oxygen saturation during high-G as compared to that of males.
- Study of female performance at high-G across the four phases of the menstrual cycle.

- Study of the effect of high-G exposure on average menstrual cycle length.

Background

Female Cardiovascular Adaptation to High-G

Failure to effectively regulate blood pressure and cerebral perfusion during high-G aircraft maneuvering could lead to reduced performance in pilots. Regular training at high-G enhances G-tolerance while prolonged layoff from exposure in high-G profiles (G-layoff) can result in reduced G-endurance [6]. However, physiological mechanisms associated with adaptation to chronically repeated high-G exposure (G-training) and subsequent G-layoff have not been identified. Since impaired blood pressure regulation following exposure to low gravity is associated with increased compliance of the lower leg [7, 8, 9], impairment of cardiac baroreflex responses [10, 11, 12, 13, 14, 15] and lower stroke volume [16,17], it is reasonable to hypothesize that improved performance with high-G training may be associated with enhanced autonomic and cardiovascular functions. However, the assumption that training in combat-oriented aerial maneuvers in high-performance aircraft improves cardiovascular mechanisms associated with blood pressure regulation lacks experimental evidence.

With the inclusion of females into fighter aircraft, little or no data exist on female adaptation to the high-G environment. Recent data reported from several investigations provide evidence that females have lower tolerance to various orthostatic challenges compared to males [18, 19,20], and that these differences are associated with differences in blood pressure regulation in females [21, 22]. Lower orthostatic capacity could clearly compromise the performance of the female warrior under combat conditions, especially in high performance aircraft. Based on their lower orthostatic tolerance, it is reasonable to hypothesize that females may benefit to the same degree or more than males from training in high-G environments.

In conjunction with the female performance study described in our previous DWHRP report [5], we measured changes in baroreflex function, limb compliance, and hemodynamic responses to an orthostatic challenge before and after training at high-G acceleration in men and women. The purpose of this research was to test the hypothesis that physiological functions associated with blood pressure regulation are enhanced by increased G-exposure independent of gender.

Female Cardiac Function after Chronic Exposure to High-G

Positive G_z has been shown to decrease venous return to the heart producing vasoconstriction with elevated aortic pressures [23, 24]. The use of positive pressure breathing and anti-G straining maneuvers help improve venous return while increasing cardiac afterload. The magnitude of the actual transmural pressure gradients have been debated since studies by Burns et al., have demonstrated that elevated pressures in the great vessels are accompanied by concomitant increases in the intrathoracic pressure [25]. Although the actual degree of cardiac stress under $+G_z$ may not be clearly defined, there is agreement that the cardiac workload is increased. Concerns about the chronic effect of such stresses has stimulated studies to evaluate subtle changes in cardiac function and chamber size as evaluated by echocardiogram.[26] Three

prior studies have evaluated various echocardiographic parameters of subjects exposed to high $+G_z$ in the centrifuge or fighter aircraft as compared to matched controls.

In 1985 Ille et al., reported echocardiographic differences in a group of French Mirage 2000 pilots compared to a group of matched control transport pilots [27]. They found significant differences in the systolic dimensions of the left atrium and in the thickness of the ventricular septum. The third and most significant difference was in the right ventricular dimension. In 1989 Vandebosh and Vastesaege presented preliminary results of a longitudinal study of F-16 pilots [28]. They found no changes in echocardiographic parameters after a period of six years. Gray reported echocardiographic changes in his group's regular centrifuge subjects compared to matched controls [29]. In this instance, the changes were not found in the parameters described as significant by Dr. Ille's group, but in two different areas; the presence of mitral regurgitant jets and the presence of E/A reversal with valsalva.

The main objective of this part of our study was to longitudinally evaluate echocardiographic parameters in a group of centrifuge subjects using each subject as his/her own control. We used this information to address the parameters identified as significant in previous studies which used matched controls. A second objective was to evaluate any gender differences in the effect of $+G_z$ exposure on the echocardiogram. Our objective was to evaluate the null hypothesis stating that there would be no change in the echocardiographic measurements of our subjects following DES exposure compared to pre-exposure measurements. Furthermore, no difference was expected in the response of female subjects compared to male subjects.

Female Isometric Strength and Acute High-G Exposure

The introduction of women into the high performance fighter aircraft arena has raised many issues concerning pilot strength and stamina and its relationship to maintaining consciousness during air-to-air combat. There is no disputing the fact that women on average are about 50 percent as strong as men in upper body strength [30]. It has been speculated that the difference in strength between men and women would compromise a woman's ability to perform in a high-G environment, and that this difference in strength may lead to early muscle fatigue resulting in compromised physiology during exposure to high-G. This study examined isometric strength capabilities of men and women both prior to and immediately following the completion of four high-G simulated air-to-air combat.

Female Oxygen Saturation During Exposure to High-G

One area of investigation where data are limited is the study of cortical tissue oxygenation responses to $+G_z$ acceleration. Glaister first reported data concerning the status of tissue oxygen levels in the cerebral cortex during $+G_z$ acceleration [31]. Over the past eight years the technology for measuring cerebral oxygenation changes noninvasively and transcranially has been refined and miniaturized making subject/patient monitoring an almost effortless process. The device used in this study is a commercially-available cerebral oximeter which uses continuous-wave two-wavelength near-infrared spectroscopy to monitor changes in regional oxygenation in the adult cortex. It was specially modified by the manufacturer to withstand the rigors of the multi-axis G-environment.

Near-infrared and infrared light, which penetrates human tissues quite well, can be used to measure the oxygen level of arterial blood, while other devices can measure regional cerebral tissue oxygenation *in situ*. Hemoglobin selectively absorbs certain wavelengths of light depending on whether it is oxygenated or reduced, making it possible to evaluate the quantities of each species..

In 1987, Eggert and Blazek [32] demonstrated that near-infrared and infrared light can penetrate through the scalp and skull and into the cerebral tissue. Chance and Delpy demonstrated the technique of "diffuse transmission spectroscopy" [33, 34], where a light path penetrates the cranium, is reflected in all directions, and is then detected by an ipsilateral sensor.

The principles described above were used in the development of the device used in this study (INVOS 3100, Somanetics Corp., Troy, MI). Figure 1 illustrates the use of two single wavelength LED light sources which emit light that scatters in all directions throughout the tissue. The closer (shallow penetration depth) detector receives light which has traversed through the skin, shallow subcutaneous tissue and the cranium, and some brain tissue. The further detector receives light from the extracranial tissues as well as relatively more cerebral tissue. Several studies have been accomplished to validate this technology. Bagian et al. [35] and Arnold et al. [36] tested the INVOS 3100 using graded hypoxia. According to the authors, the ability of this cerebral oximeter to measure rapid changes in tissue oxygen saturation makes it a viable candidate for monitoring subjects exposed to +G_z acceleration on a human centrifuge. Further technical details of the theory of operation of this device can be found in its operation manual [37] and in the AMRL Technical Report [38].

Effect of Menstrual Cycle Phase on Female Performance at High-G

The medical literature, as well as the popular literature, support the view that women undergo cyclic symptoms during the menstrual cycle such as bloating, irritability, and breast tenderness. However the meaningful question to be addressed is whether women's performance of mission critical tasks is affected. Table 1 briefly lists recent relevant studies that have addressed performance as a function of menstrual phase and oral contraceptive use. Most concern physical exertion, such as exercise, and a few concern precision tasks and cognitive function. None of the cited studies combine both, as is necessary in the high-G fighter cockpit. Two studies have addressed gender differences in G-tolerance [39, 40], but neither addressed menstrual phase, use of oral contraceptives, or performance.

Effect of High-G Exposure on Menstrual Cycle Length

Anecdotal evidence from our subject pool suggested an alteration of the cycle length during months in which high-G exposure occurred. It was hypothesized that some stress reaction or hormonal release resulting from high-G stress altered the normal hormonal surges and resulted in early menses. The purpose of this portion of the study was to determine if a scientific analysis of cycle length versus G-exposure supported this belief.

Author	Year	Independent Variables	Dependent Variables	Finding
Hudgens, Fatkin, Billingley, & Mazurczak [41]	1988	Sex, MP, OC, Practice, Handgun Wt	Hand steadiness	All treatments significant
Fine & McCord [42]	1991	OC, Caffeine, Visual Field Dependence	Color discrimination	All treatments significant, but inter-actions confounded
Lebrun, McKensie, Prior, & Taunton [43, 44, 45]	1995	MP	Aerobic/anaerobic capacity, Strength, Endurance	Aerobic Capacity slightly decreased by ovulation phase
Davies, Elford, & Jamison [46]	1991	MP	Handgrip, Standing long jump	Both measures significantly superior during menstruation
Kanaley, Boileau, Bahr, & Misner [47]	1992	MP, Menstrual Status	Metabolic substrate conc.	MP has no negative effect on meta-bolism during sub-maximal exercise
Hampson [48]	1990	MP	Fine motor skill, Spatial ability	Phase affects both measures, skill up and spatial down compared to menses baseline

Table1- Relevant research. MP = Menstrual Phase OC = Oral Contraceptives

BODY

Facility

This research was conducted on a ground-based human centrifuge, the Dynamic Environment Simulator (DES), located at Wright-Patterson AFB, OH. The DES is a research facility which couples simulated high-G with flight simulator capability that provides the means to measure psychophysiological, behavioral, and subjective reports of mission performance, workload, and situation awareness [49].

Subjects

Sixteen active duty non-rated Air Force volunteers (8 men, 8 women) were recruited and passed the rigorous medical screening procedures including spinal and cranial radiographs, blood analysis, and neurological examination. All were briefed on the study, signed an informed consent, and received an anti-G suit, helmet and mask fitting, and anti-G straining maneuver training. Experimental procedures and protocols were approved by the Human Utilization Research Committee at Armstrong Laboratory, Wright-Patterson Air Force Base.

The effects of acceleration on a pregnant woman are virtually unknown, and the risks of injury to the woman cannot be ignored [50]. Also, the effects of acceleration on a developing

fetus are little known and the potential for fetal injury, malformation, or even death may be significant [51]. For these reasons, pregnancy precluded participation in this acceleration research.

Methods

Physiologic Adaptation

Seven women with a mean (\pm SE) age of 27 ± 2 years, weight of 58.9 ± 3.1 kg and height of 165 ± 3 cm and six men with age of 24 ± 1 years, weight of 76.7 ± 4.3 kg and height of 177 ± 4 cm served as subjects. Subjects underwent a series of tests for assessment of baroreflex function, limb compliance, and hemodynamic responses to an orthostatic challenge before and after training at high-G acceleration.

On experimental days, subjects reported to the laboratory wearing a T-shirt and jogging shorts in order to undergo their tests for cardiovascular function. After each subject was placed on an 8-ft exam table in a supine position, the upper and lower left calf was instrumented with band electrodes with application of Aquasonic electrode gel over the area where the electrodes were to be placed. This provided better coupling between the electrode and the subjects skin. A thigh blood pressure cuff was placed on the thigh just above the left knee. The electrodes were then connected to a Minnesota Impedance Cardiograph model 304B (Minneapolis MN). Continuous heart rate was recorded using a modified five-lead electrocardiogram. In addition, an Ohmeda 2300 Finapres® photoplethysmographic finger blood pressure cuff was placed on the middle finger of the subject's left hand. Heart rate and blood pressure responses were saved as digital data.

Following the initial instrumentation procedure, subjects performed Valsalva maneuvers at an expiratory pressure of 30 mmHg in the supine posture to provide an index of baroreflex function according to a technique previously described [52]. Each trial included a 30-s baseline period followed by a 15-s strain period, and a 2-min post-strain period. A small leak in the system prevented the subject from maintaining the expiratory pressure by occluding the glottis. Trials were separated by two minutes of rest. The average of three trials was calculated to represent the response for each subject. Subjects were instructed to remain quiet and still during both the baseline and post-strain collection periods. Following baseline collection, the subject was asked to give a ready signal at the end of a normal inspiration. At this point, the subject began blowing into a mouthpiece connected to a calibrated pressure transducer (Propper Analog Manometer). After 15 s at 30 mmHg expiratory pressure, the subject released pressure and breathed normally after the mouthpiece was removed. An aneroid gauge positioned in front of the subject provided feedback on the expiratory pressure. Expiratory pressures were measured continuously and beat-to-beat heart rate and mean arterial pressure were estimated with the Finapres® finger plethysmographic device. Excellent estimates of directly measured intraarterial pressures during Valsalva maneuvers have been demonstrated with this device [53].

Following the Valsalva maneuver test, calf compliance was measured applying venous occlusion with an impedance plethysmographic technique [54]. Subjects remained in the supine position and an occlusion cuff placed around the thigh, just above the knee, was inflated to 60 mmHg for 120 sec. The subject was instructed to remain as still as possible during this procedure. Changes in impedance, i.e., volume, were recorded using a Clevite Mark 220

(Cleveland OH) two-channel brush recorder. Leg compliance was calculated by dividing the volume change at a plateau, i.e., point at which venous pressure equals cuff pressure, by the cuff pressure and expressed as ml/mmHg. The value for leg compliance was multiplied by 100 for convenience.

Following the leg compliance test, subjects were asked to stand so that they could be instrumented for the squat-stand test. Four silver tape electrodes, two placed around the neck and two placed around the thorax, were attached to a Minnesota Impedance Cardiograph (Model 304B) for non-invasive rheographic determination of beat-to-beat stroke volume[54] during the final 10 sec of squat and the initial 10 sec of standing. This instrument introduced a frequency of 50 kHz at a low constant current (1 mA R.M.S.) into the thorax through the outside electrodes and detected changes in electrical impedance of the thorax with each pulse beat across the inner pairs of receiving electrodes. Cardiac output was calculated as the product of heart rate and stroke volume and systemic peripheral resistance was calculated by dividing mean arterial pressure by cardiac output. Subjects remained instrumented from the previous test and were asked to place the hand with the Finapres® finger blood pressure unit on their chest at heart level. Subjects were instructed to assume a squatting position for a 4-min time period. Impedance and blood pressure data were collected continuously throughout this test. The subjects were then instructed to stand erect as quickly as possible without using their hands to assist them. Data were collected for 30 seconds after standing. All physiological data were stored on a Tandy 4000 microprocessor.

Measurement of Baroreflex Responses to Valsalva Maneuver

Data from the three trials were averaged in a phase-by-phase manner for baseline, phase I, early phase II, late phase II, and phase IV [52, 55]. Blood pressure responses (Δ MAP) for each phase were calculated as follows: *phase I*) peak MAP during early straining - baseline MAP; *early phase II*) peak phase I MAP - lowest mid-strain MAP; *late phase II*) peak late strain MAP - baseline MAP; and *phase IV*) peak post-strain MAP - phase III MAP. Changes in heart rate were calculated using the same phase-by-phase method employed for Δ MAP. For phase I, Δ MAP was used in the analyses as an index of vascular volume [56]. For late phase II, Δ MAP was used in the analyses as a marker for sensitivity of baroreflex-mediated control of peripheral vascular resistance[57]. The ratio Δ HR/ Δ MAP was used in the analyses for early phase II and phase IV because of its usefulness in describing integrated cardiac baroreflex responsiveness [58].

G-Exposure History

Each subject underwent a total of 8 days of high-G exposure with peak acceleration plateaus at 4-5 G on days 1 through 4, followed by gradual increase to peak acceleration plateaus at 6, 7, 8, and 9 G on days 5, 6, 7, and 8, respectively. Training profiles on days 4-8 involved four open loop simulated aerial combat. These training profiles were 100 to 135 sec in duration. After the eight days of indoctrination training, subjects had been exposed to over 45 minutes of acceleration greater than 2 +G_z.

Statistical Analysis

Analysis of covariance (ANCOVA) was used to analyze this two group (male, female) by two repeated measures (pre-post G-training) design. This approach to the analysis of simple pre-post repeated measures experiments identifies the differences in pre-post gain scores between males and females after adjusting for pre G-training variation. As suggested by Laird [59], this statistical model attempts to correct for changes in pre-post measures that are influenced by initial pre-treatment values (i.e., regression toward the mean). The result is a mean gain score for each gender statistically adjusted for the baseline level (pre G-training) of each subject. Confidence intervals are placed around the adjusted means and were used to evaluate differential changes from pre to post G-training between males and females. Because directional changes in heart rate and mean arterial pressure responses to the Valsalva maneuver associated with G-training were predictable, one-tailed tests were applied. The null hypothesis was rejected when $p < 0.05$.

Cardiac Examinations

Twenty-four subjects successfully completed the medical screening examination for the panel. Eleven of these new panel members were male and thirteen were female. None of these individuals had a history of significant prior exposure to high $+G_z$. A baseline echocardiogram was performed in the cardiopulmonary clinic at Wright-Patterson Medical Center using a Hewlett Packard (Palo Alto, CA) Sonos 1500 or Sonos 2000 echocardiograph with a 2.5 or 3.5 MHz ultrasound transducer. The subjects were enrolled in an 8 session indoctrination training program described in the G-history section of adaptation methods above. The time for completion of the indoctrination varied by subject from a minimum of 9 weeks to a maximum of 22 weeks. Eighteen subjects successfully completed the indoctrination study (seven males and eleven females) and had a second echocardiogram completed. After completing all the echocardiographic studies, they were read by a cardiologist who was blinded to the order in which the studies were performed. The results of the evaluation for mitral regurgitant jets were evaluated using a Fisher's Exact Test. The remaining primary and all secondary parameters were evaluated using a one sided T-Test. The Male-Female comparisons were evaluated using ANOVA.

Primary and Secondary Cardiac Parameters

The parameters in Table 2 have been identified as significant in previous studies and, thus, they were the primary parameters for our study. A significant difference in these parameters was considered confirmatory of previous work. Any significant differences in the remaining parameters could not be considered to represent anything other than the starting point for a future prospective study. The secondary measurements were additionally recorded as part of each echocardiographic evaluation. Although none of these values had been identified as significant in prior high $+G_z$ studies, they are part of our facility's standard echocardiogram evaluation covering the spectrum of clinically significant findings.

PRIMARY MEASUREMENTS	SECONDARY MEASUREMENTS
<ul style="list-style-type: none"> • LEFT ARTERIAL DIAMETER • VENTRICULAR SEPTAL THICKNESS • RIGHT VENTRICULAR DIAMETER • E/A REVERSAL WITH VALSALVA • E/A REVERSAL WITHOUT VALSALVA • PRESENCE OF MITRAL VALVE REGURGITATION 	<ul style="list-style-type: none"> • END SYSTOLIC VOLUME • END DIASTOLIC VOLUME • FRACTIONAL SHORTENING • STROKE VOLUME • EJECTION FRACTION • LEFT VENTRICULAR SIZE IN SYSTOLE • LEFT VENTRICULAR SIZE IN DIASTOLE • LEFT VENTRICULAR POST WALL THICKNESS • RIGHT ATRIAL DIAMETER • AORTIC ROOT DIAMETER

Table 2. Primary and Secondary Cardiac Parameters

Strength Testing

Fourteen subjects participated including 8 males and 6 females ranging in age from 21 to 41 (mean age 27 years). Subjects were dressed in a standard issue flight suit and boots for all tests. All subjects met the JPATS or F-22 aircraft occupant standards for height and weight [60].

Test Equipment

The strength test equipment used in this study was a custom made semi-automatic static ergometer which measured isometric strength of subjects manipulating simulated aircraft controls. Figure 2 shows a subject sitting in the device in a standard test position. The test device was comprised of two components, the examiner's control/display unit and the subject test station. The control display unit sat upon a countertop positioned so that the test subject could not see the results of the test. The control unit allowed the operator to select the test condition and direction to be evaluated. The LED display provided a 3 second average of isometric strength in pounds. The five second test period started automatically when the subject applied force exceeding 5 pounds on a hand control and 25 pounds to the foot control assembly. None of the aircraft controls being tested moved but isometric forces were measured via strain gauge force transducers of 4448 N (1000 pounds) capacity.

The hand control evaluated in this study was the yoke type aileron/elevator control simulated by three hand grip positions located on top of a vertical column. The handle centers were 356 mm (14 inches) above the seat reference point which is typical for aircraft. The two outside handles which represented an aircraft control yoke and were located 178 mm (7 inches) to the left and right of center. This assembly measured forces when subjects pushed forward and pulled backward on the yoke. The yoke also measured forces generated while turning the yoke clockwise and counterclockwise. Leg strength was measured using a foot pedal assembly which pivoted on a roller bearing about a vertical axis. This design limited testing to one leg at a time.

The seat had 1 inch of foam padding and was adjustable in the fore and aft directions. The seat back angle was 13 degrees aft of vertical and the seat pan was tilted upward 5 degrees.

Strength Test Procedure

Subjects entered the testing area and were seated and secured in the aircraft seat. The seat was adjusted so that the subject's knee angle was between 130 and 140 degrees. Subjects were briefed on the testing procedures prior to performing the task. Each test condition was repeated three separate times with a two minute rest period between trials. The highest force value generated during the three trial series was used as the datum for a particular condition. Details of the testing procedure can be found in Tripp & Chelette, 1996 [61.] Test conditions were randomized across subjects. Strength tests were performed prior to entering the centrifuge and immediately following centrifugation.

Coincident with an eight visit indoctrination series that introduced motion sickness coping strategies, anti-G straining techniques, positive pressure breathing, and DES safety procedures, subjects completed 8 to 20 classes in the static simulator learning to fly and complete the multiple tasks. Then each subject underwent a minimum of three days of training that blended high-G endurance with the flight simulation.

After each subject demonstrated their ability to safely and reliably fly the closed loop simulation, they were assigned to the experiment. The schedule was mapped out for weekly runs (approximately, as scheduling allowed) to include a minimum of 3 blend days (blending G-tolerance with flight simulation) or until their performance was consistent (Standard Error of the Mean of tracking score < 1000 ft.). Assignment to the experimental design was balanced for order, gender, and skill level.

Protective Equipment

The Combined Advanced Technology Enhanced Design G Ensemble (COMBAT EDGE) with the standard CSU/13-BP anti-G suit was used because that is what is now deployed in the F-15 and F-16. COMBAT EDGE is an assisted positive pressure breathing system that includes an oxygen regulator that provides 12 mmHg per G pressure to the aviator's mask beginning at 4 G. Maximum pressure is 60 mmHg at 8 G and above. Also included is a counter pressure vest that inflates with the same pressure schedule to compress the chest as lung pressure is increased. An air bladder in the helmet also inflates in order to aid mask tightness to prevent mask leakage. The COMBAT EDGE system is explained in [63]. Protective equipment was customized to accommodate both men and women. In operational scenarios these types of modifications are common practice [31, 33]. Five women and six men reduced the height of their anti-G suit abdominal bladders. Arm pain has been a by-product of PBG protection, especially in the centrifuge, thus four women and six men elected to wrap their arms to avoid arm pain.

Oxygen Saturation Measurements

Following a pre-acceleration examination by the flight surgeon, and the donning of a flight suit, the subject was ready for instrumentation. Prior to the application of the cerebral oxysensor, the subject's right sinus was trans-illuminated to rule out an oversized sinus area which could interfere with NIR transmission. At this point, the subject's forehead was cleaned with isopropyl alcohol and the self-adhesive sensor was placed on the right side of the forehead, immediately below the hair line. An elastic bandage was then applied around the subject's head giving additional stabilization to the cerebral sensor. A Nellcor RS-10 oxysensor (Nellcor

Incorporated, Pleasanton CA.) was placed under the elastic bandage on the left side of the forehead over a branch of the superficial temporal artery. Percent arterial oxygen saturation and heart rate were recorded using a Nellcor N-200 pulse oximeter. Details of the testing procedure can be found in Tripp & Savul, 1996 [38]

Data for each of the variables was recorded continuously during the test and analyzed using standard statistical methods. Mean values and standard deviations were calculated for pre-test baseline, at the point of maximal change and 30-seconds post-test. Mid- and end-point values were compared with pre-test baselines to generate relative change. Groups were compared using the paired t-test; $p < 0.05$ was considered significant.

Simulated Air-To Air Combat Sortie

The Dynamic Environment Simulator is configured with a wide field-of-view visual display, shown in Figure 3, for presentation of a closed-loop flight task where subjects control the onset/offset of high-G according to the requirements of the flight. A computer generated, projected, instrument panel was installed and controlled by specialized software. The subjects were tasked to perform the following:

- Maintain controlled flight
- Follow lead, maintain 3000 ft range (tail chase)
- Discriminate call-sign and correctly respond
- Report any 5000 ft altitude breaks
- Upon klaxon, find and evade missile (Attitude, Chaff, Direction, max G)

Metrics for mission accomplishment included the measurement of closed-loop flight performance, overall + G_z dose, and reaction times/error rates to secondary tasks related to the mission. Performance metrics were measured for two initial 1 G runs (normal 1 G environment) followed by four real-G runs (DES arm active) with three minute rest periods between each run. The multifaceted task included not only pursuit tracking, but speech discrimination, choice response, altitude reporting, and missile evasion. Each 3 minute engagement was designed to emulate an air-to-air targeting sortie. The target aircraft profile was randomly selected from a library of profiles prerecorded to contain similar G-dose and maneuvers of equivalent difficulty.

Mission Completion Analysis

Mission completion was defined as four complete high-G sorties with scores appropriate to their training level, and the subject did not quit, lose consciousness, or otherwise cancel any part of the mission. The null hypotheses to be tested was that cycle phase does not affect mission completion rate.

An analysis of source variance was conducted to determine if mission success was affected by phase of the menstrual cycle. Because actual ovulation day or days menstruation was not tracked, cycle phase was defined by quarters of each women's mean cycle. Chi squared testing was used to determine if the distribution of successes or failures was unusual in any quarter.

Menstrual Cycle Analysis

Eight women participated in this performance study over several months. During this time, each women had two or three months in which they did not pull high-G and five or six months in which they participated in the described performance study. The women were grouped by their contraceptive status; four women were on oral contraceptives and four were not. Both groups (oral contraceptive users and non-users) were tested to determine if the variability of cycle length was affected by exposure to high-G.

RESULTS

Female Cardiovascular Adaptation to High-G

The results for hemodynamic responses to the squat-stand test are presented in Table 3 and Figures 4 and 5. The change in posture from squat to standing reproduced an average reduction in total peripheral resistance of 8 to 12 pru (Fig. 4), which did not differ between males

	Post-Pre Stand Test Differences	SE	95% CI
Total Peripheral Resistance, pru			
Males	-4.0	2.6	[-9.9, 1.8]
Females	0.5	2.4	[-4.9, 5.9]
Heart Rate, bpm			
Males	-0.3	2.5	[-5.84, 5.22]
Females	3.0	2.3	[-2.1, 8.1]
Stroke Volume, ml			
Males	14.0	5.3	[2.2, 25.9]
Females	-0.5	4.9	[-11.5, 10.5]
Cardiac Output, l/min			
Males	1.3	0.5	[0.1, 2.4]
Females	0.4	0.5	[-0.7, 1.4]
Mean Arterial Pressure, mmHg			
Males	-10.0	3.9	[-1.4, -18.6]
Females	-5.5	3.6	[2.5, -13.4]
Δ HR/ Δ MAP, bpm/mmHg			
Males	0.2	1.6	[-0.2, 0.6]
Females	0.3	1.5	[-0.1, 0.6]
Baseline Calf Impedance, ohms			
Males	-2.6	4.7	[-13.0, 7.9]
Females	6.3	4.3	[-3.2, 15.8]
Calf Compliance, Δ ml/ Δ mmHg			
Males	15.0	4.5	[4.9, 25.2]
Females	7.3	4.2	[-2.0, 16.6]

Table 3. Mean differences between pre- and post-G training in hemodynamic responses to standing in males (N = 6) and females (N = 7). SE = standard error of the mean and 95%CI = 95 percent confidence interval. Note: Bolded confidence intervals do not include zero. Mean differences are adjusted for pre-G training differences (ANCOVA).

and females before and after G-training (Table 3). Likewise, the elevation in heart rate caused by standing was similar before and after G-training (Fig. 5) in both males and females (Table 3). During the move from squat to standing, males increased stroke volume and cardiac output after G-training compared to the pre G-training response, while these responses remained relatively unchanged from pre-to-post G- training for females (Table 3). The increased stroke volume and cardiac output in males during standing after G-training was associated with less reduction in mean arterial pressure compared to the females who demonstrated a similar hypotension both pre and postG-training (Fig. 4). No differential changes in the ratio between the change in heart rate and change in mean arterial pressure ($\Delta HR/\Delta MAP$) induced by standing were observed between males and females, although both groups increased $\Delta HR/\Delta MAP$ after compared to before G-training (Fig 5).

Heart rate and blood pressure responses to the Valsalva maneuver are presented in Table 4 and responses during early phase I and phase IV are presented in Figure 6. Differences between males and females from before and after G training were minimal. Although the confidence interval for the change from before to after G training in $\Delta HR/\Delta MAP$ during early phase I and phase IV marginally included zero (Table 3), 8 of 12 male and female subjects demonstrated an increase in these responses (Fig. 6).

Baseline impedance of the calf increased from 23.1 ± 3.8 to 30.9 ± 4.4 ohms in the females, but was reduced from 36.3 ± 4.2 to 30.4 ± 4.0 ohms in the males (Fig.). Calf compliance increased by 146% in males and by 90% in females after compared to before G training.

Valsalva Maneuver Phase	After - Before G Training Differences	SE	95% CI
Phase I ΔMAP			
Males	1.4	1.8	[-2.6, 5.4]
Females	2.6	1.8	[-1.4, 6.6]
Early Phase II $\Delta HR/\Delta MAP$			
Males	0.3	0.2	[-0.2, 0.7]
Females	0.2	0.2	[-0.2, 0.6]
Late Phase II ΔMAP			
Males	-0.2	3.9	[-9.0, 8.5]
Females	-3.3	3.9	[-12.0, 5.5]
Phase IV $\Delta HR/\Delta MAP$			
Males	0.4	0.2	[-0.2, 0.9]
Females	0.3	0.2	[-0.3, 0.8]

Table 4. Mean differences between pre- and post-G training for changes in heart rate (ΔHR) and mean arterial blood pressure (ΔMAP) in males (N = 6) and females (N = 6) during the four phases of the Valsalva maneuver. SE = standard error of the mean and 95%CI = 95 percent confidence interval. Note: Mean differences are adjusted for pre-G training differences (ANCOVA).

Female Cardiac Function after Chronic Exposure to High-G

No significant differences were detected in any of the primary or secondary echocardiographic parameters in our subjects following the completion of indoctrination training (Tables 5, 6, 7). The results of evaluation for mitral regurgitant jets before and after the

completion of indoctrination training are listed in table 5. Furthermore, ANOVA did not detect a difference between the response of our male and female subjects.

MEASUREMENT	PRE EXPOSURE		POST EXPOSURE		COMPARING PRE AND POST EXPOSURE MEASUREMENTS (P VALUE)	ANOVA P VALUE
	MEAN	VARIANCE	MEAN	VARIANCE		
• LA DIAMETER	3.42 cm	0.17	3.47 cm	0.25	0.32	0.71
• SEPTAL THICKNESS	0.81 cm	0.03	0.80 cm	0.02	0.44	0.28
• RV DIAMETER	4.01 cm	0.32	4.19 cm	0.30	0.11	0.34
• E/A REVERSAL WITH VALSALVA	2.07 cm	0.41	2.21 cm	0.62	0.28	0.81
• E/A REVERSAL WITHOUT VALSALVA	2.09 cm	0.32	1.91 cm	1.02	0.27	0.22
• PRESENCE OF MR	N/A	N/A	N/A	N/A	>.05	>.05

Table 5. Primary Parameters Echocardiographic Data

MEASUREMENT	PRE EXPOSURE		POST EXPOSURE		P VALUE
	MEAN	VARIANCE	MEAN	VARIANCE	
• END SYSTOLIC VOLUME	51.9 cc	346	42.3 cc	354	0.25
• END DIASTOLIC VOLUME	132 cc	1387	136 cc	1335	0.25
• FRACTIONAL SHORTENING	34%	23	36%	30	0.10
• STROKE VOLUME	82.6 cc	610	87.3 cc	550	0.13
• EJECTION FRACTION	62%	41	65%	55	0.10
• LEFT VENTRICULAR SIZE IN SYSTOLE	3.42 cm	0.23	3.37 cm	0.30	0.31
• LEFT VENTRICULAR SIZE IN DIASTOLE	5.19 cm	0.42	5.31 cm	0.36	0.17
• LEFT VENTRICULAR POST WALL THICKNESS	0.77 cm	0.02	0.81 cm	0.01	0.16
• RIGHT ATRIAL DIAMETER	3.56 cm	0.17	3.72 cm	0.25	0.09
• AORTIC ROOT DIAMETER	2.82 cm	0.14	2.92 cm	0.15	0.09

Table 6. Secondary Cardiac Parameters

SEX	MR BEFORE	MR AFTER
F	TRACE	NONE
F	TRACE	TRACE
F	NONE	TRACE
F	NONE	TRACE
F	TRACE	MILD
F	TRACE	NONE
F	NONE	NONE
F	NONE	NONE
F	NONE	MILD
F	MILD	NONE
F	NONE	NONE
M	TRACE	MILD
M	NONE	NONE
M	NONE	NONE
M	NONE	NONE
M	MILD	MILD
M	NONE	NONE
M	NONE	NONE

Table 7. Incidence of Mitral Regurgitant Jets

Female Isometric Strength and Acute High-G Exposure

No significant changes in strength were observed within groups of men or women when comparing pre-rested upper (Table 8) and lower body strength to post-G strength measures. There were, however, significant differences in strength between both groups. Women were 53 percent as strong as the men. Despite the significant differences in baseline strength measures between men and women, there were no statistically significant differences in maximum isometric strength post-G acceleration.

	Yoke Left	Yoke Right	Yoke Forward	Yoke Backward
Men Pre-G	118 ± 22	126 ± 24	234 ± 52	211 ± 26
Men Post-G	104 ± 22	110 ± 17	248 ± 24	218 ± 32
Women Pre-G	54 ± 18	59 ± 21	105 ± 30	114 ± 27
Women Post-G	58 ± 15	65 ± 19	144 ± 40	128 ± 29

Table 8. Mean Upper Body Strength PRE- and POST-G (lbf)

Female Oxygen Saturation During Exposure to High-G

Figure 7 is a single sortie which is representative of the subject's physiological response during the 180 second exposure to +G_z. A between group comparison of cerebral oxygen saturation revealed that the decrease in rSO₂ in females was significantly less than that in males. A comparison of pre-acceleration rSO₂ to the minimum rSO₂ values measured during the +G_z show a decrease of 13% (men) and 9% (women) from pre-acceleration values (Figure 8). Post-baseline analysis of rSO₂ also showed significant differences between genders. Again the

mean change in women's rSO₂ values was significantly less than was seen in the men. Within group comparisons showed significant changes in rSO₂ comparing pre-baseline rSO₂ to minimum values measured during acceleration $p \leq 0.001$) and to post-baseline values $p \leq 0.001$).

A regression analysis of rSO₂ for acceleration exposures above +8 G_z demonstrated the regional cerebral tissue oxygen desaturation rate for females to occur at a slower rate than for males (slope = -0.34 %/sec, $p = 0.04$ and slope = -0.71 %/sec $p < 0.001$ respectively). These data also demonstrate that exposure to high-G had a lesser effect on female cerebral tissue oxygenation compared to their male counterparts. (Figure 9)

There were no significant changes in SaO₂ between groups. Significant changes in SaO₂ were seen when comparing pre-baseline values to the minimum values measured during acceleration within groups of men and women and $p < 0.001$), respectively.

No significant differences in heart rate were observed between groups, however there were significant changes in heart rate observed within groups during +G_z and post-G for men and women and $p < 0.001$), respectively.

Simulated Air-To Air Combat Sortie

Self Induced G-Dose

The integral under the profile curve but above 3 G is an indicator of the self imposed dose of G. The 3 G lower limit is necessary due to the non-linear relationship of the aero-model and the DES response below 3 G. Analyzing by groups showed that gender had no effect on the amount of G that the subjects commanded. One G simulation versus simulation with G stress did not influence the commanded G in men. However, the women commanded significantly higher G loads when the load was not real (in 1 G simulation). When the G stress was added, the women endured a G dose equivalent to men.

Additional examination using the number of seconds in each G range as a response variable, showed that there was a significant difference between genders in the time spent above 8 G (Figure 10). Females spent an average of 15 seconds in that range, while males spent an average of 10 seconds per sortie.

Effect of Menstrual Phase on Mission Completion

Table 9 represents the days of the cycle horizontally. Each woman's mean cycle length ends at the start of the black lines. The first and third quarters are shown in gray highlighting. Note the upper group were not on oral contraceptive, while the lower group was. The number of successes and failures per quarter are tabulated at the bottom. Chi square testing indicates that the successes and failures are equally distributed across the cycle.

Another important finding of the present study was that men demonstrated cardiovascular adaptation to high-G training while women did not. While high-G training increased stroke volume, cardiac output, and protected against orthostatic hypotension following compared to before G-training during the squat-stand test in the men, it failed to alter any of these cardiovascular . It is possible that female pilots may have less physiological potential to adapt their cardiovascular functions during training leading to aerial combat.

In the present study, we used the beat-to-beat hemodynamic response during the initial time interval (less than 10 sec) of standing immediately following four minutes of a squat posture as an orthostatic challenge designed to assess cardiovascular function before and after G-training. We are unaware of any previous documentation that describes the use of this test in research or clinical application. An immediate pronounced reduction in total peripheral resistance occurred upon standing, representing an apparent reactive hyperemia induced by a tourniquet effect of the squat position. Since the initial response of sympathetically-mediated peripheral vasoconstriction requires 2-3 sec to occur [62] with maximum effect requiring approximately 10-15 sec [63], hemodynamic responses within 10 sec of standing probably were not influenced by baroreflex functions during this procedure. As a result, the squat-stand protocol provided a highly reproducible cardiovascular stimulus (i.e., reactive hyperemia-induced hypotension) before and after G-training in both males and females (Fig. 1). These data suggest that this orthostatic protocol could provide an excellent repeatable diagnostic or screening technique for clinical application and field operations in addition to its research potential.

Calf compliance was dramatically increased following G- training in both men and women in the present investigation. This finding was unexpected since we hypothesized that high-G acceleration would induce adaptations that would enhance cardiovascular function for blood pressure regulation. The mechanism of increased compliance in our subjects is unclear. Increased compliance has been observed following exposure to low gravity and was associated with reduction in the muscle compartment (tissue and water) that surrounds the veins [7]. However, the absence of statistically discernible changes in baseline impedance in both males and females following G-training (Table 3) suggested that increased venous compliance in the calf was not associated with loss of muscle compartment. An alternative explanation for increased venous compliance following G-training is the possibility that the veins and/or their valves may have become damaged by the repeated exposure to extremely high hydrostatic pressures under acceleration. Our observation that increased calf compliance following G- training may be the first data to support a hypothesis that chronically repeated exposure to high-G acceleration may cause structural damage to veins of the lower extremities and compromise venous return during orthostatic challenges.

Aircrew of high performance aircraft have reported that resumption of high +G_z flying after extended time away from +G_z exposure (G-layoff) is accompanied by a period of reduced tolerance or performance. Empirical data have recently been obtained from recent experiments that corroborate these observations [6]. The adaptations in cardiovascular function following G-training in the present study may provide a physiological basis for the phenomena of G-layoff.

Our eight sessions of +G_z exposure did not produce significant changes in cardiac function or chamber size as measured by echocardiogram. In addition, no significant differences were detected between the responses of male and female subjects. Changes described in previous studies may be due to greater cumulative exposures in those studies or to additional variation due

to their use of matched controls. Reevaluation of our subjects with further +G_z exposures is needed. To clarify the answer; however, the current data help to better define a safe level of G-exposure for centrifuge subjects and help reassure Air Force pilots regarding the possible long term risks associated with flying high performance aircraft.

Results from this study showed no significant reduction in strength within groups of men or women when comparing pre G-exposure to post G. These data may have far reaching effect on Air Force Global Reach Policy where aircrew are moved to transatlantic or transpacific locations and are then required to perform air-to-air combat missions in support of combat operations. These data may also be useful for commanders in the field when making decisions whether to re-launch a pilot who has already been involved in limited air-to-air combat but, who reports subjective fatigue.

Analysis of changes in rSO₂ by gender showed that female cerebral cortex tissue desaturations were smaller than those same measures in males during high-G exposure. This difference in cerebral rSO₂ may be related to several different factors including differences in eye to heart distance between the two genders, cerebral tissue oxygen consumption during task performance, and better cerebral tissue perfusion. In addition, at 30 seconds post-G, rSO₂ was slow in recovering to pre-acceleration values. Recovery of SaO₂ was relatively rapid after the gravitational force was unloaded from the subject and SaO₂ values showed full recovery to the pre-test baseline at 30 seconds post-acceleration.

These cerebral tissue oxygen saturation results may be of importance to the aeromedical community from the stand point of aircrew performance during high-G maneuvering, such as following an air-to-air combat engagement. The cerebral oximeter performed extremely well in the high-G environment after 512 exposures to G levels ranging between 7 and 9 G_z. The self-adhering sensor was easy to apply and did not interfere with the wearing of the flight helmet. This was also true of the pulse oximeter, and, with the exception of having to apply an elastic bandage to hold the sensor in place, there were no failures of this device in any of the acceleration exposures. Both the pulse oximeter and cerebral oximeter provided valuable insight into the psychophysiological response in the high-G-environment.

Gender Effect Summary

The gender related results of the three experiments concerning cardiovascular adaptation to G, cerebral oxygen saturation, and multi-task cognitive performance need to be considered as a package. In summary, the research team found that:

- during indoctrination training, women's bodies did not provide adaptation to the G while men's bodies did provide adaptation.
- during G-exposure, women displayed less loss of oxygen content in the arterial-venous mix of blood within the cerebrum
- overall, women did not perform the air-to-air combat task as well as the men, even though they pulled just as much G.

We believe these results to be consistent under the following model. The lack of physiological adaptation to G (no increase in cardiac contractility or baroreceptor sensitivity) meant that women had to strain harder to pull the same G and experienced more transient visual symptoms. Both of these requirements would lead to less cognitive capacity to perform the

combat task. The women apparently did not extract oxygen from the cerebrum in the same proportions as the men; this may contribute to the lower tracking scores achieved by the women as a group. The men were capable of more cognitive workload since they were getting more reflexive help from their bodies.

Thus the oxygen findings were a result of the lower cognitive processing, and the lower cognitive processing capability was a result of the lack of G adaptation. In this view, the women should be commended on their valiant effort in the face of reduced physiological adaptation. Immediate research to test these hypotheses is essential to find out what the appropriate G adaptation training schedules should be for women, and to verify the oxygen consumption model vs. cognitive performance.

A smaller reserve for cerebral ischemia may be an alternative interpretation to the lesser reduction in rSO₂ with lower performance scores during acceleration in females compared to males. It is not unusual for males to have an average blood hemoglobin (Hb) concentration of 16 g/dl compared to an average of 12 g/dl in females [64]. Given that the oxygen-carrying capacity of 1 g Hb is 1.34 ml O₂, the average female can transport only about 75% (16.1 ml O₂) of the 21.4 ml O₂ that the average male can transport per unit (100 ml) of blood. Furthermore, since the average blood volume of females can be 17% less than that of males [65], it is possible that total O₂ carrying capacity of the blood in females may be as much as 62% less than that of males. Under these conditions, it would be reasonable to expect that only 68% of the reduction in rSO₂ in males (13%) would be required to produce similar cerebral ischemia in females (9%). These numbers match our observations and would be consistent with the observation that the females in the present study had lower performance scores coincident with lesser reduction in rSO₂ during acceleration. Therefore, without blood volume and hemoglobin concentration data to refute this hypothesis, we cannot dismiss the possibility that reduced performance with less loss of rSO₂ may represent a smaller reserve (tolerance) for cerebral ischemia in female subjects.

Specific Operational Recommendations

With positive pressure breathing for G, good mask fit is essential not only for G protection but for communication clarity. A positive pressure mask leak results in a loud squeal that could compromise communication, and thus mission completion. With the addition of women to the fighter pilot ranks, the range of face shapes is significantly increased such that it is unlikely a set of sizes can be derived that will accommodate all. We recommend continued support of the quick turn-around, low cost, volume custom mask making efforts that are currently under development at Brooks AFB.

There is considerable interest in furthering the research on the gender differences in adaptation to G. It is possible that women may need a longer period of time or a more rigorous schedule in order to achieve equivalent adaptation to G. There is also considerable interest in trying to determine if the gender differences found in oxygen delivery can be accounted for physiologically. However, at this time the only operational recommendation that can be made is that all pilot trainees be given generous amounts of exposure and repetitions prior to solo flying at high G.

Related Manuscripts Submitted

The following manuscripts have been submitted to Aviation, Space, and Environmental Medicine, the journal of the Aerospace Medical Association:

The Effects of Simulated Air-to-air Combat Sorties on Cerebral and Arterial Oxygen Saturation.
LD Tripp, TL Chelette, S Savul, R Widman.

The Effect of Multiple Simulated Air-to-air Combat Sorties on Isometric Strength.
LD Tripp, TL Chelette, S Bolia

Female Performance at High G: Chronic Adaptations of Cardiovascular Functions.
VA Convertino, LD Tripp, DA Ludwig, J Duff, TL Chelette

Female Performance at High G: Following Exposure to +9Gz (Echocardiography Results).
WB Albery, RP TenEyck, M Wolfe.

Discussion of Sample Size

During the portion of the study concerning cardiovascular adaptation the facility experienced some relatively brief down time (3 weeks). Though this did not compromise the entire effort, it did disrupt the novice adaptation process, thus disqualifying the data of subjects experiencing a hiatus. Fortunately, the results of this study were sufficiently robust that the reduced N size showed both statistical significance and adequate power.

Regarding the small N size in each group of women (4 OC users Vs 4 non-OC users), the small N size is due to the contractual reporting deadline. Data have been collected on 2 additional subjects and currently 6 more are in active data collection, to be completed before the end of the calendar year. The rate at which data are collected is limited both by availability of dedicated volunteers and availability of facility run time to keep each subject skilled and adapted to G. Results of the entire data set are anticipated to be presented at the annual meeting of the Aerospace Medicine Association in Seattle during May of 1998 and subsequently published in their Journal. Updates will be forwarded to the Army as well.

CONCLUSIONS

This research evaluated men and women performing complex cognitive tasks in the high-G environment. Although none of the subjects were pilots, they all learned to fly an F-16 simulation closed loop on a human centrifuge and were able to command as much G as the F-16. Neither gender showed any ill effect on cardiac function from several months of G-exposure. Both genders maintained their strength after G exposure. Women's cardiovascular systems appeared to lack the adaptation training to high-G that men's bodies provided, though both genders showed increased calf compliance after G adaptation. Women exhibited less cerebral desaturation than men at high-G. Women did not perform quite as well as men on the simulated air-to-air combat sortie, though they pulled just as much G as the men. No effect of the female menstrual cycle was found on mission completion rates and no effect of high-G exposure was found on the progression of the female cycle. Nothing was found that suggests that women should not fly high performance aircraft, however it may yet be necessary to modify the training regime or life support equipment to accommodate the special needs of female aviators.

These results suggest that pure G-tolerance or physiological measures would have concluded that the females were superior at coping with high-G, compared to the males. Yet performance metrics reveal that the women could not perform the cognitive task of an air-to-air sortie at high-G as well as the men. Thus, high-G performance metrics must be included and must be sufficiently sensitive to operational issues such as fatigue if meaningful results are to be obtained. Situational awareness and complex decision making are essential. Within this simulated sortie, the missile evasion task showed the most significant sensitivity to environmental stressors.

The views expressed herein are the private views of the authors and not to be construed as representing those of the Department of Defense or Department of the Air Force.

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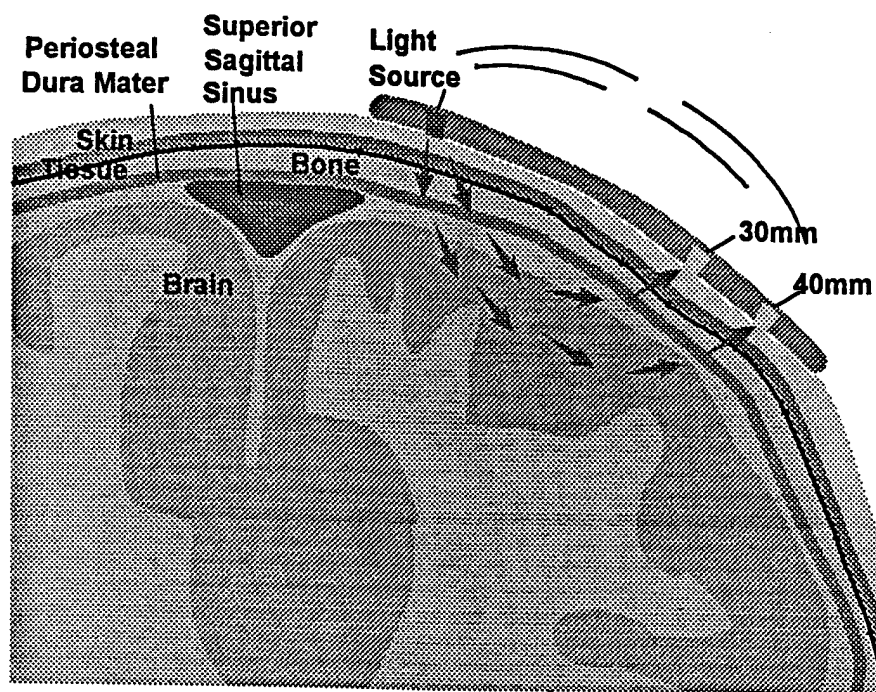


Figure 1. Somanetics INVOS 3100 principles of operation.

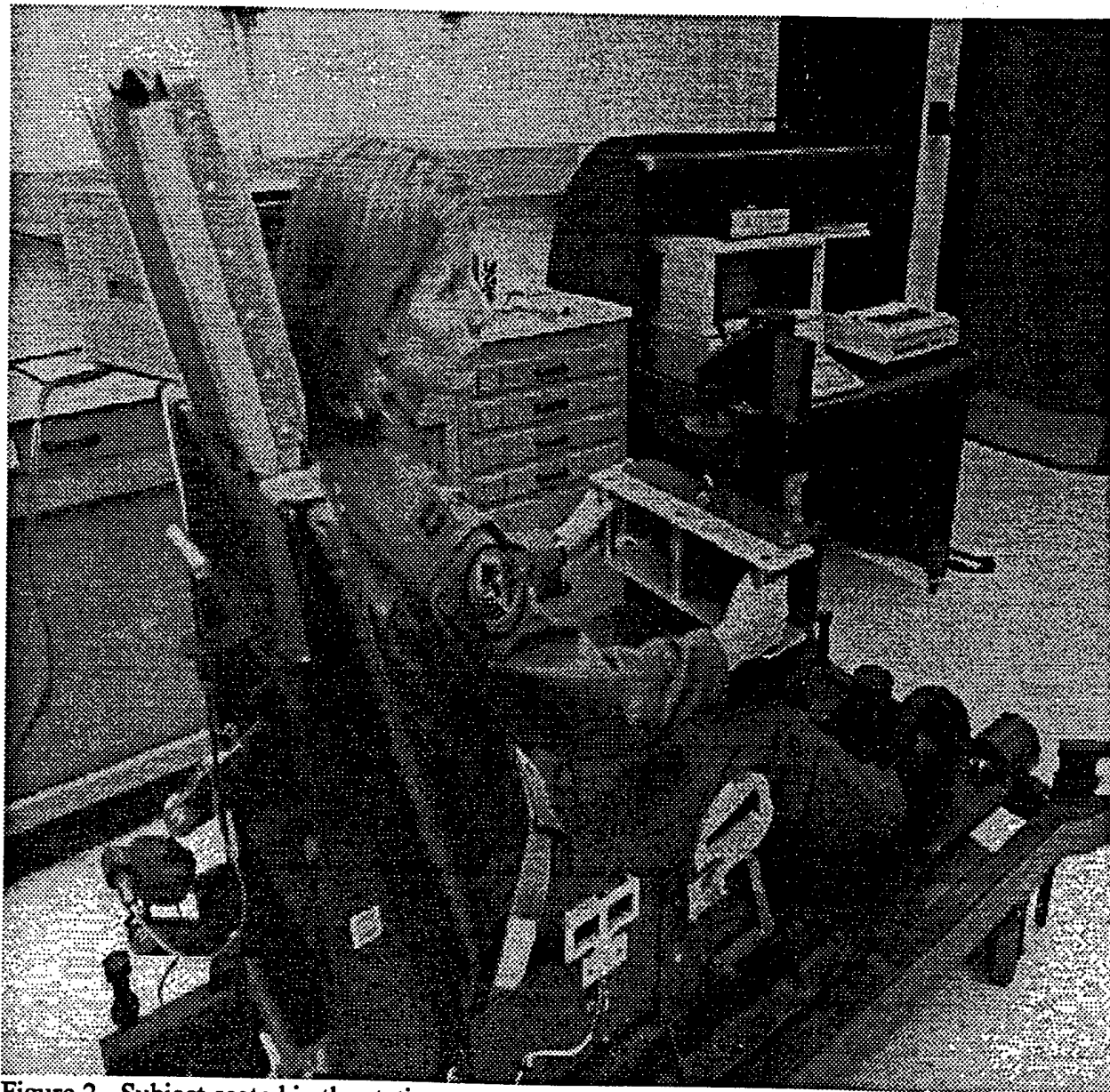


Figure 2. Subject seated in the static ergometer positioned for an upper-body strength test.

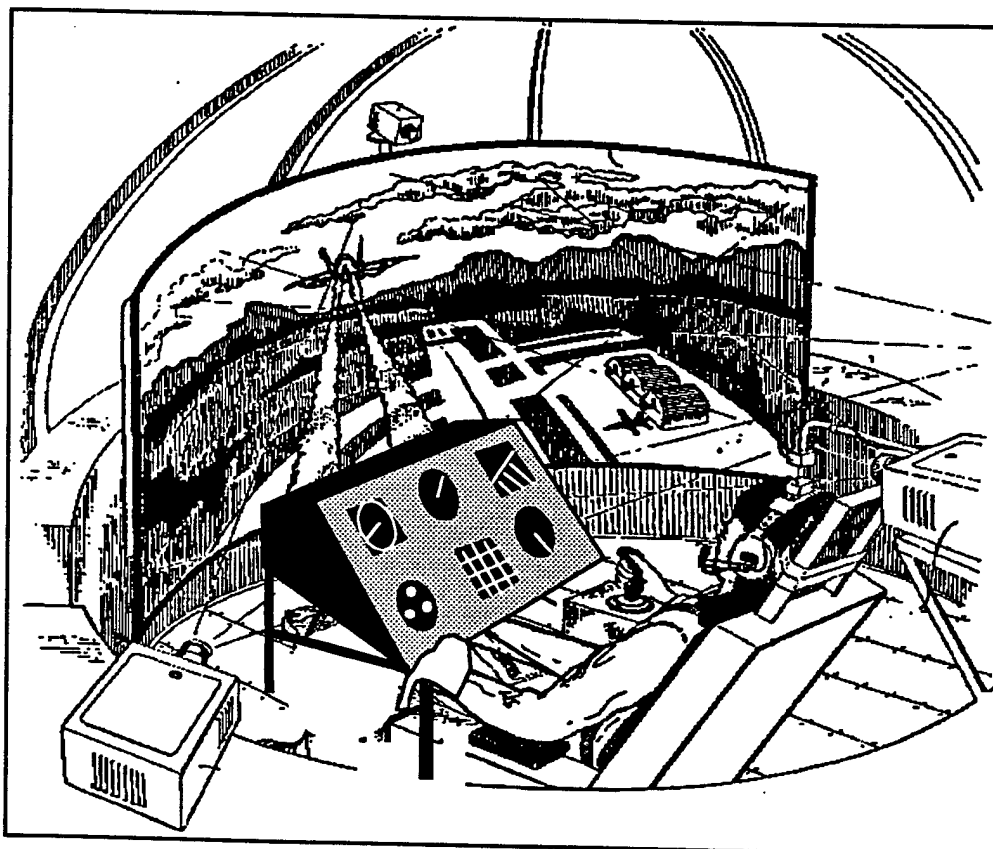


Figure 3. DES configured as a flight simulator.

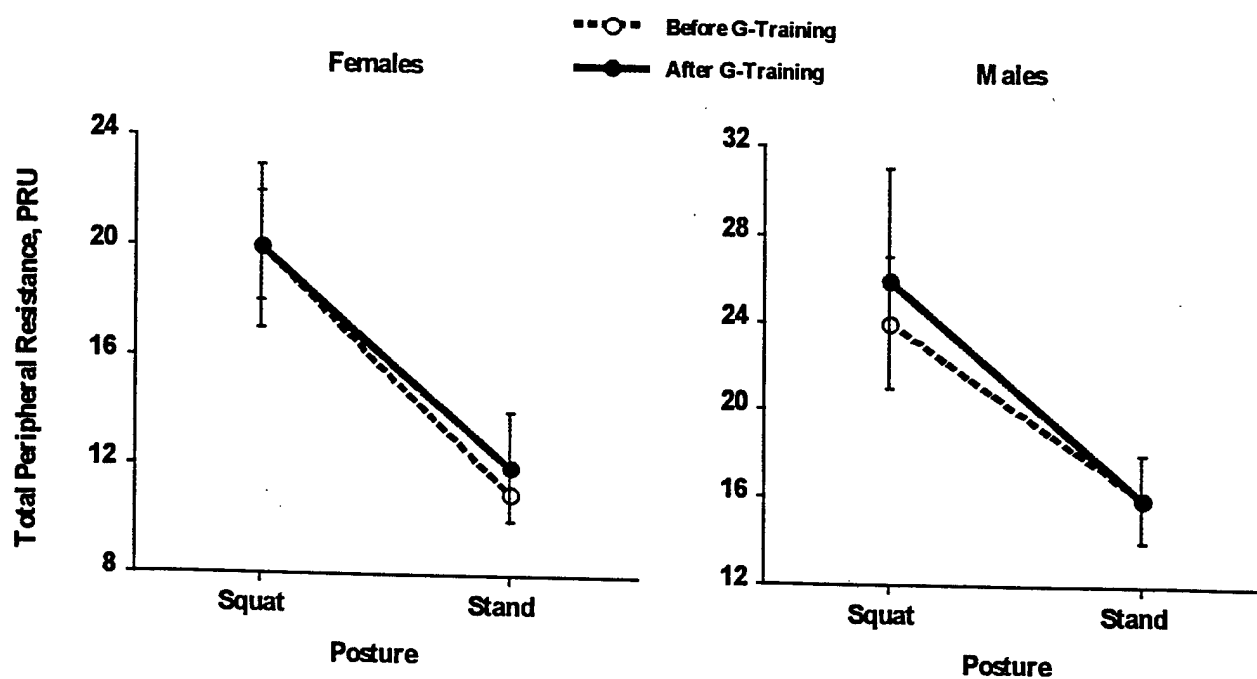


Figure 4. Total peripheral resistance during squat and stand postures in females (left panel) and males (right panel) before (open circles and broken lines) and after (solid circles and solid lines) G-training. Circles represent mean and bars represent \pm standard error of the mean values.

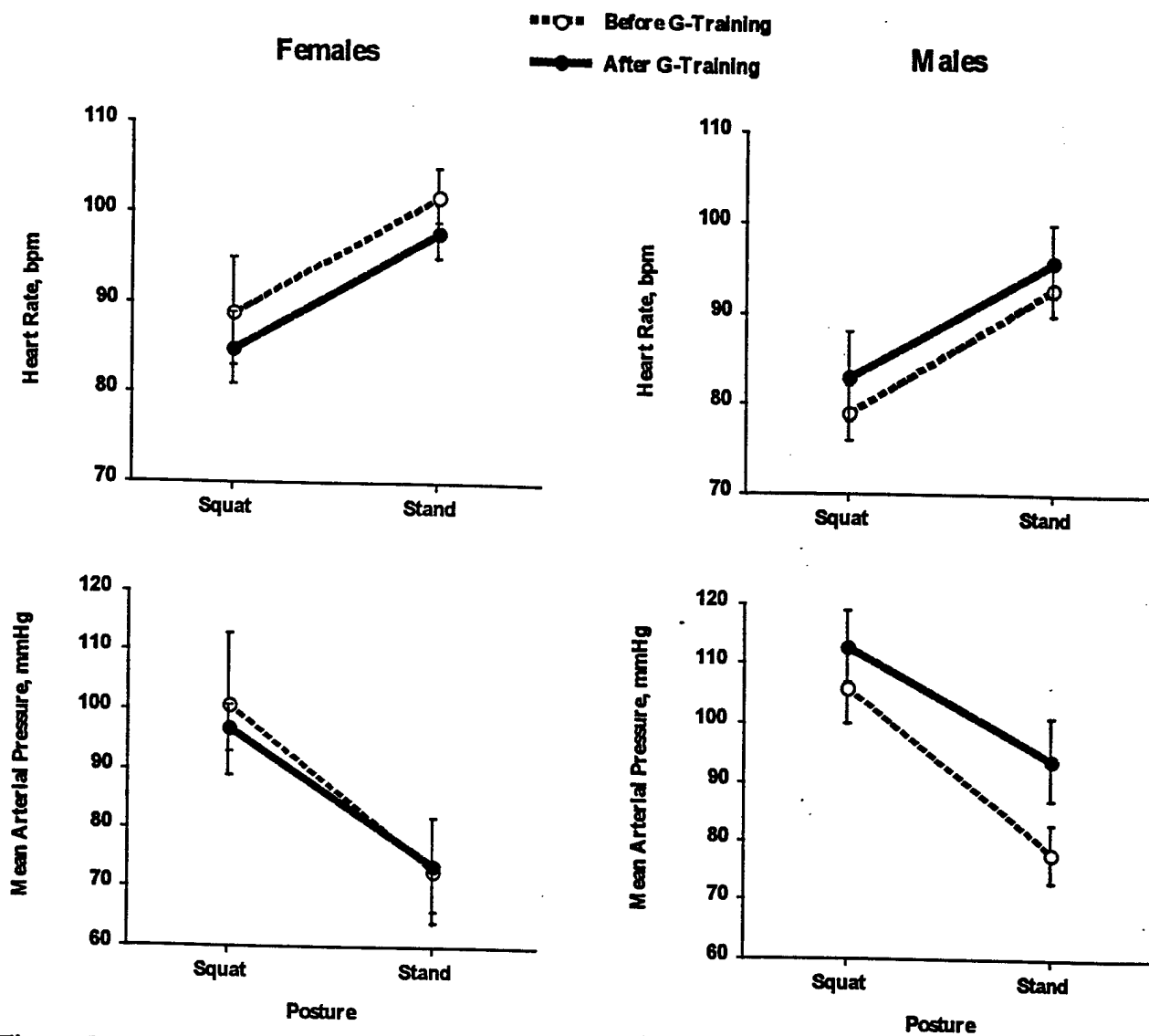


Figure 5. Heart rate and mean arterial blood pressure during squat and stand postures in females (left panel) and males (right panel) before (open circles and broken lines) and after (solid circles and solid lines) G-training. Circles represent mean and bars represent \pm standard error of the mean values.

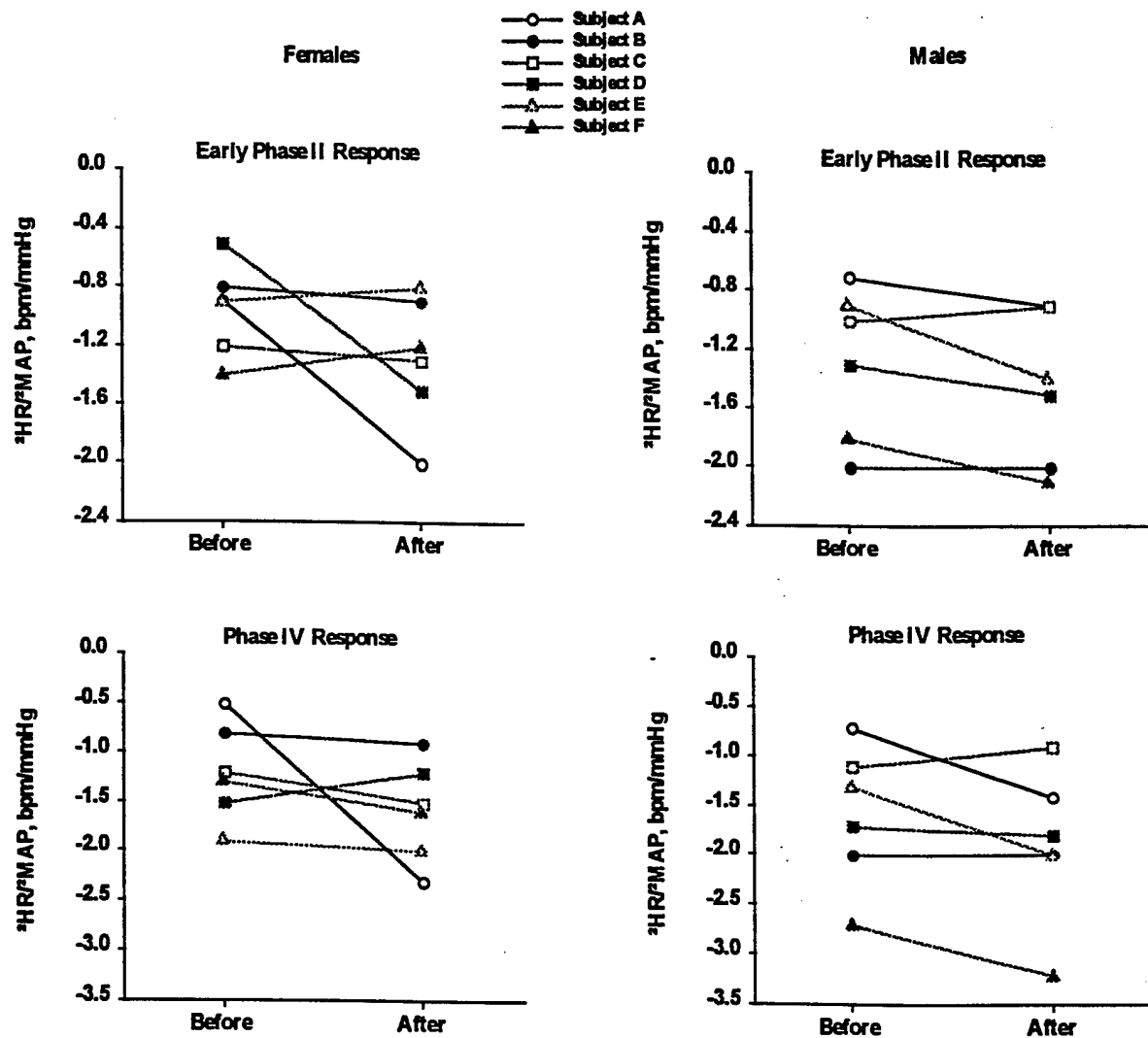


Figure 6. Ratio of the change in heart rate to the change in mean arterial blood pressure ($\Delta HR/\Delta MAP$) during early phase II and phase IV of the Valsalva maneuver in females (left panel) and males (right panel) before (open bars) and after (lined bars) G-training. Bars represent mean and lines represent \pm standard error of the mean values.

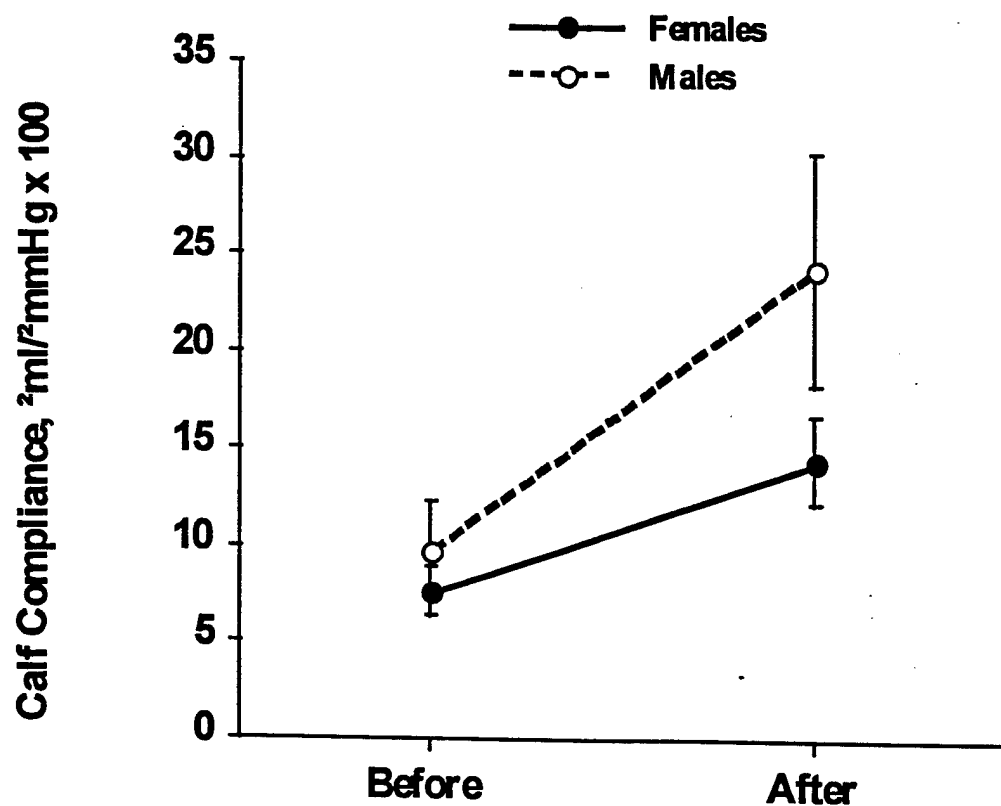


Figure 7. Calf compliance in females (left panel) and males (right panel) before (open bars) and after (lined bars) G-training. Bars represent mean and lines represent \pm standard error of the mean values.

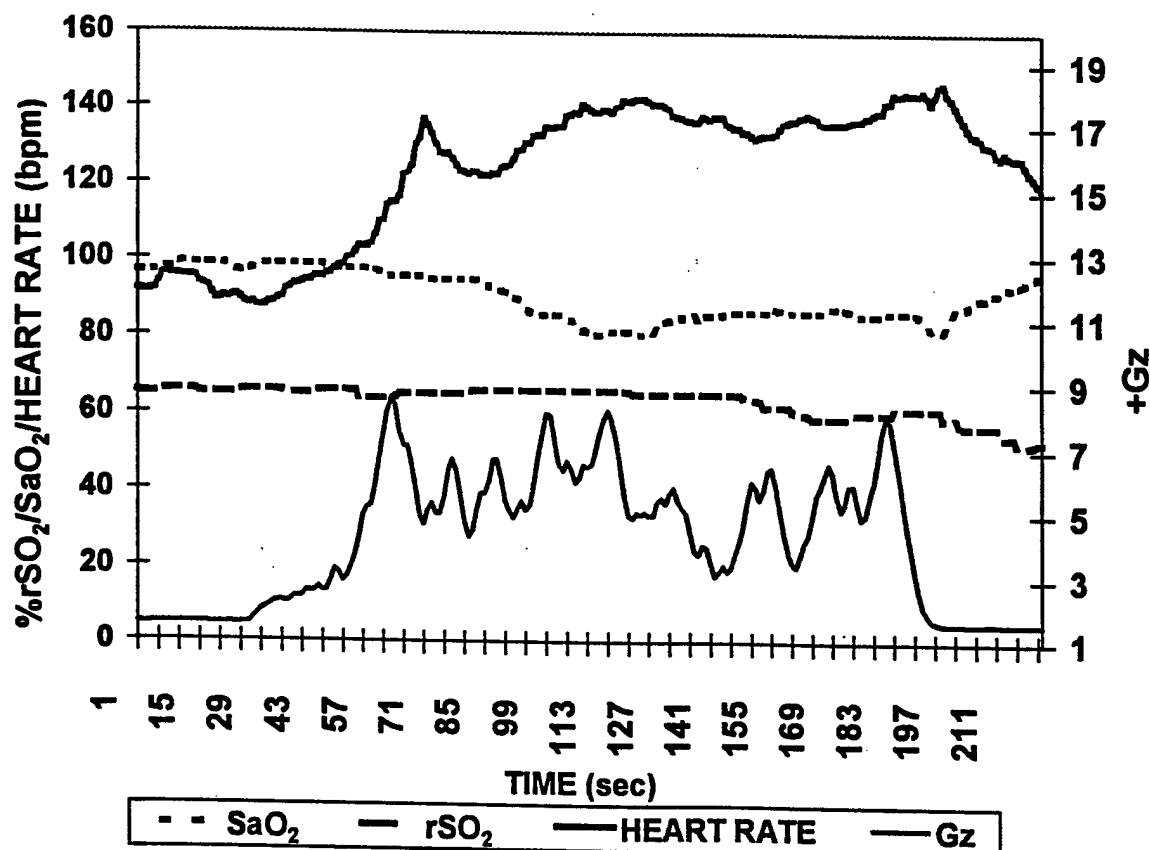


Figure 8. A typical Simulated Aerial Combat Maneuver profile from one subject.

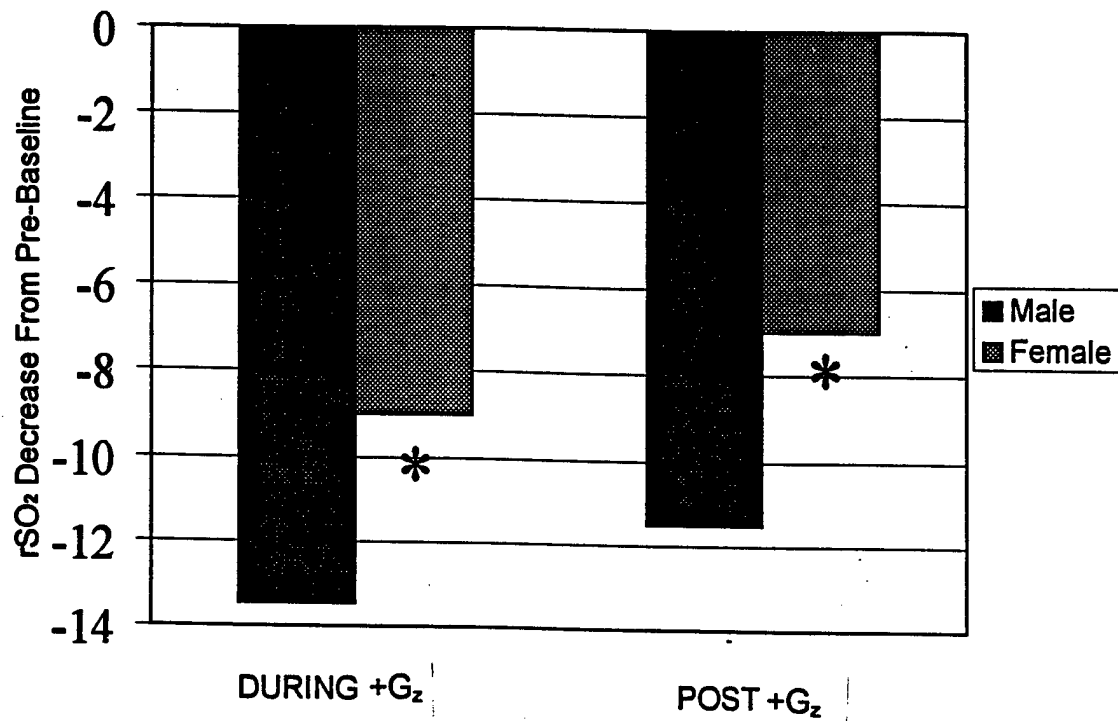


Figure 9. Cerebral tissue oxygen saturation, men and women, percent change from baseline * (p<0.01).

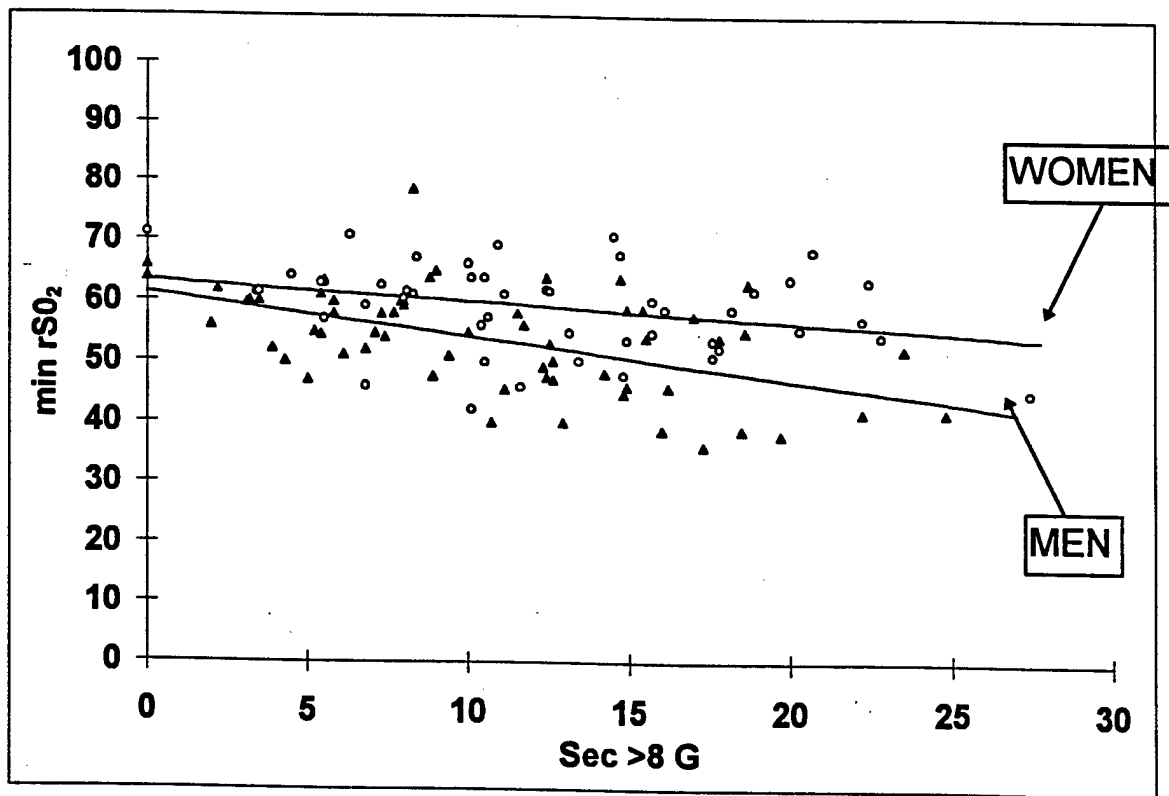


Figure 10. Regression analysis of rSO₂ between genders during time above +8 G_z. (▲ Men ○ Women)

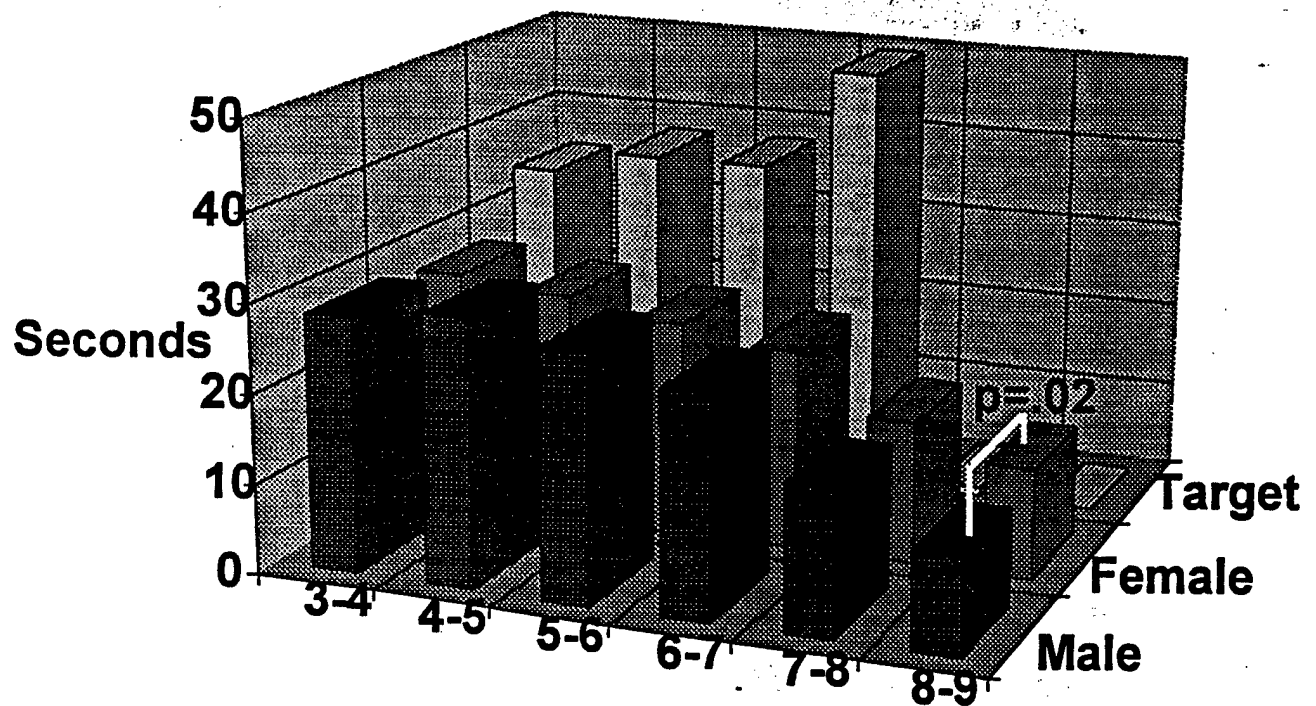


Figure 11. Mean number of seconds accumulated at each G level for both male and female pilots and the target aircraft.

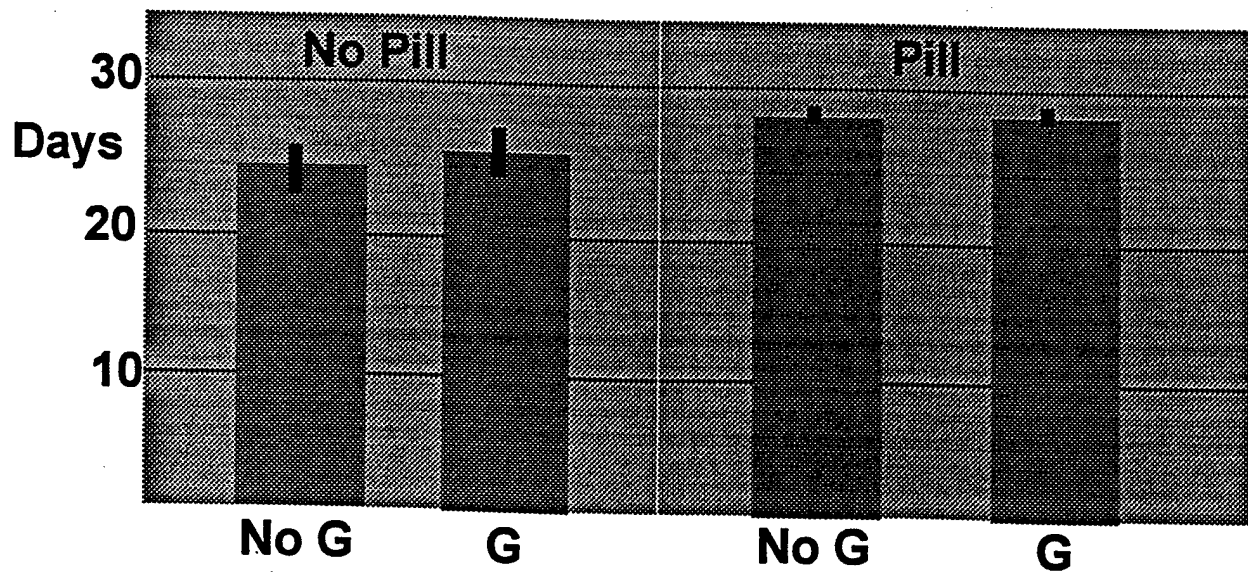


Figure 12. Cycle length for women either on oral contraceptives or no, for months with high-G and months without high-G.